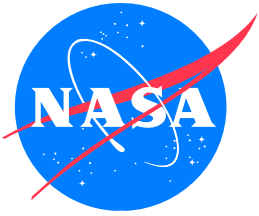


# Recent Developments on Lightweight, Flexible Dual polarization/frequency Phased Arrays Using RFMEMS Switches on Liquid Crystal Polymer Multilayer Substrates for Remote Sensing of Precipitation

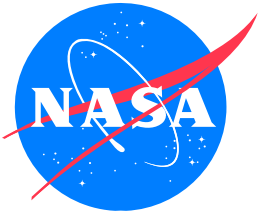
*R. Bairavasubramanian, N. Kingsley, G. DeJean,  
G. Wang, D. Anagnostou, M. Tentzeris and J. Papapolymerou  
School of Electrical and Computer Engineering  
Georgia Institute of Technology, Atlanta, GA 30332*



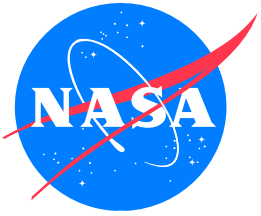
# Outline



- **Introduction**
- **LCP characterization**
- **2x2 dual frequency/polarization LCP sub-arrays**
- **RF MEMS Switches and Phase Shifters**
- **Conclusions**

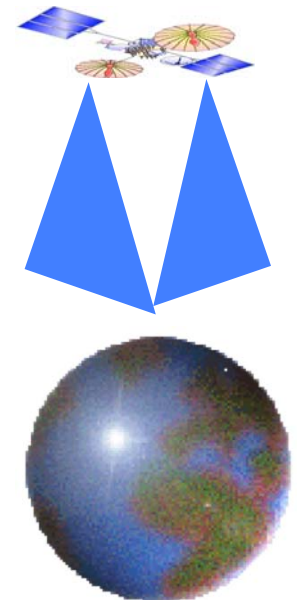


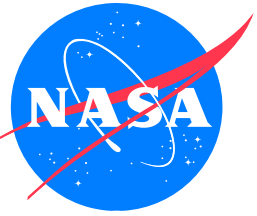
- **Introduction**
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- Conclusions



## Applicability to ESE Measurements

- Accurate monitoring and measurement of the global precipitation, evaporation and cycling of water is required to better understand earth's climate system
- Dual frequency/polarization radars are necessary to monitor precipitation patterns
- Antenna and RF front ends that have low cost, low mass, electronic scanning capabilities and are easily deployed, are preferred
- *Develop novel dual frequency/polarization array and associated electronics based on System-on-a-Package (SOP) approach*

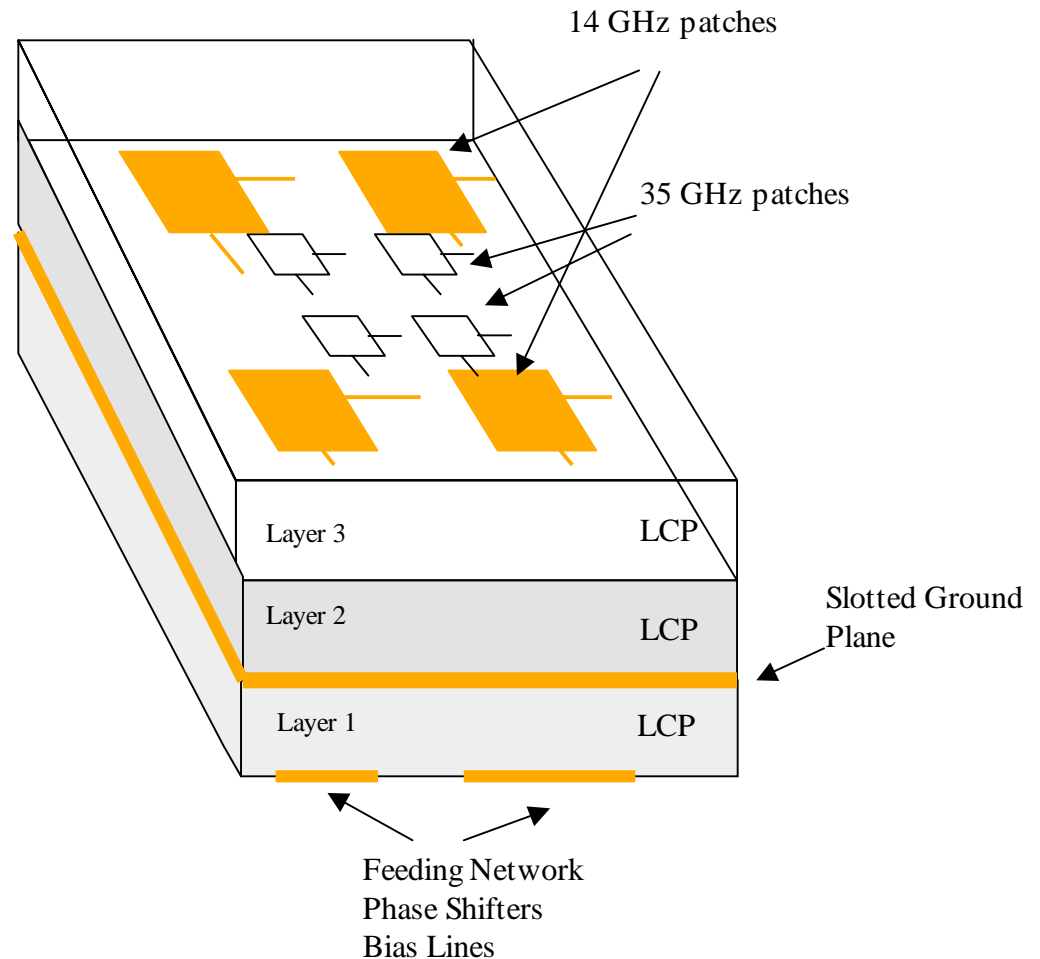


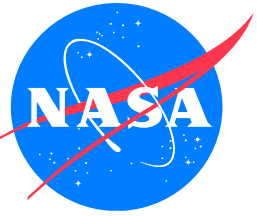


# Proposed Technology

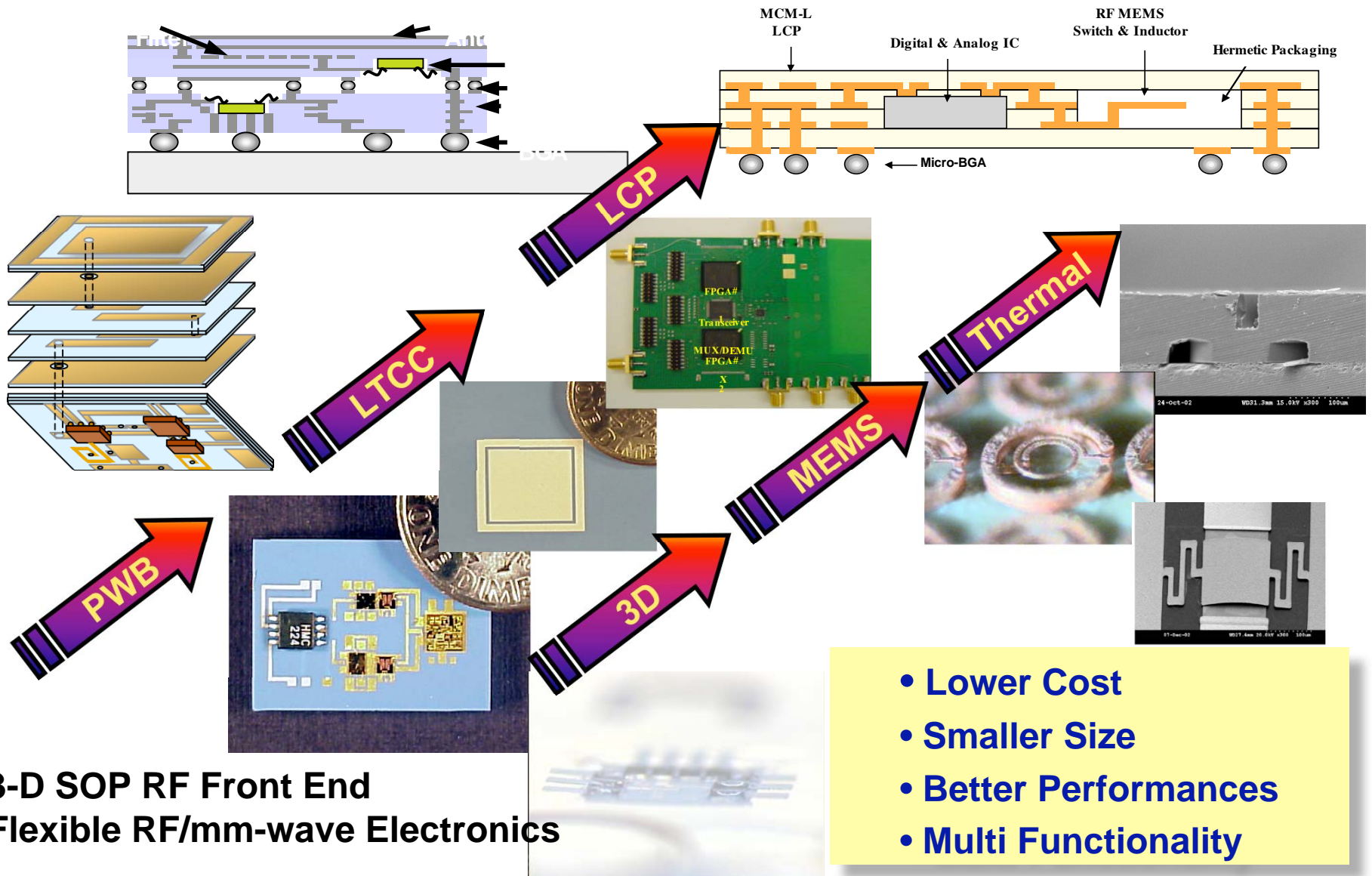


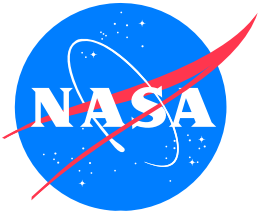
- Proposed Solution: System-on-a-Package (SOP) RF Front End
- Investigate multi-layer, low cost Liquid Crystal Polymer Technology (LCP)
- Two sets of microstrip antennas on different layers: 14 GHz array on one layer and 35 GHz array on other layer (two combinations were investigated)
- Planar and vertical feeding networks and interconnects
- Usage of integrated RF MEMS phase shifters for electronic scanning



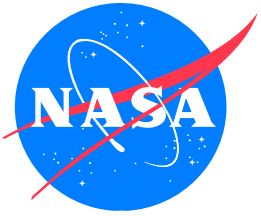


# Enabling Technologies in the future





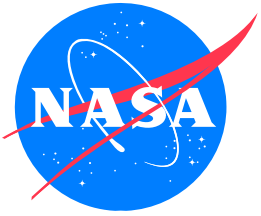
- Introduction
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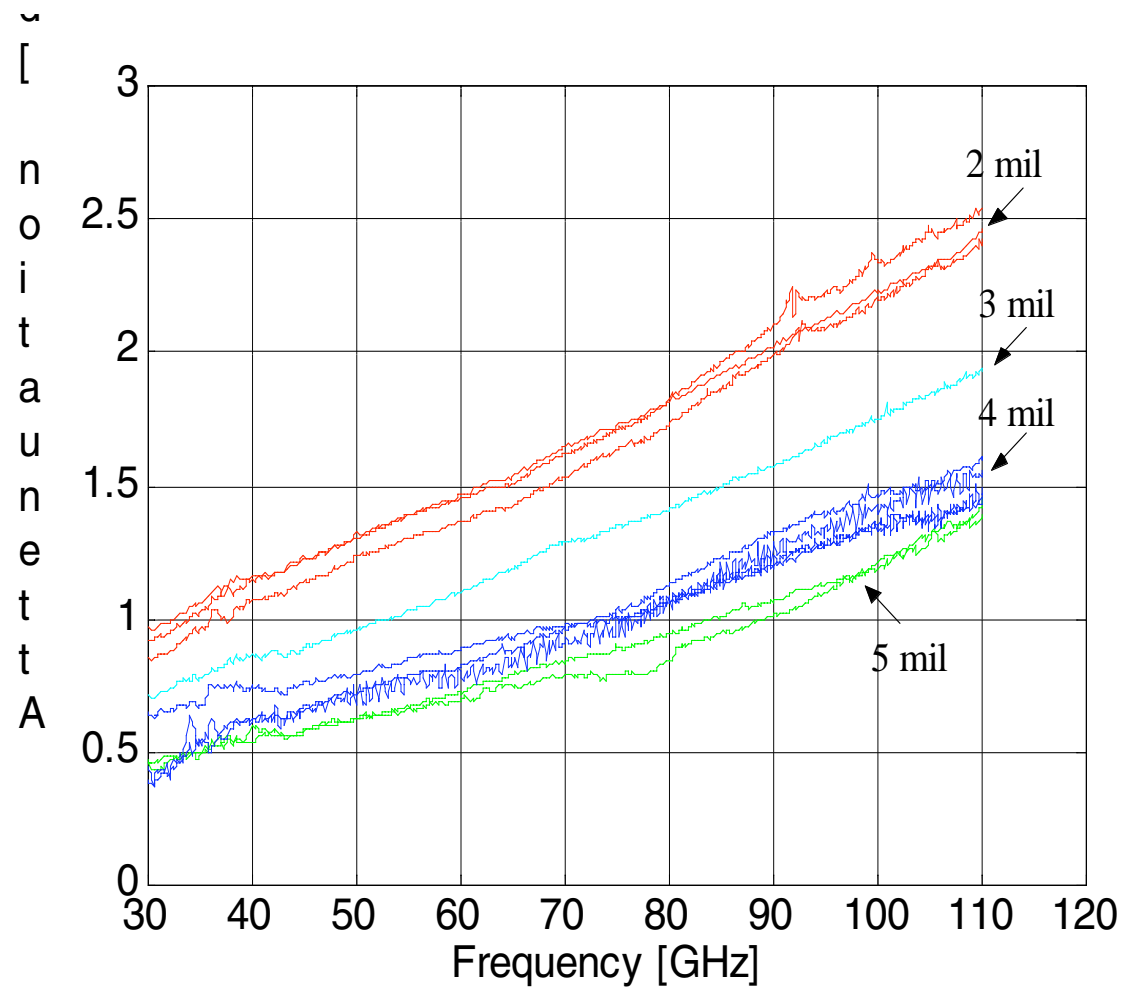
## Why LCP?



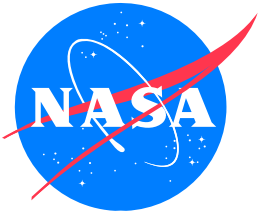
- Electrically:  $\epsilon_r \sim 3$ ,  $\tan \delta = 0.002-0.0045$  (2-110 GHz)
- Its near hermetic nature suits it as both a mm-wave substrate and package
- Low moisture permeability ( $<0.04\%$ )
- LCP films from 25 – 100  $\mu\text{m}$  thick can be conveniently laminated for multilayer structures used in system on package (SOP) designs
- Low cost ( $\sim \$5/\text{ft}^2$ )
- Micromachining ability
- Tailoring of CTE (4-30 ppm/ $^{\circ}\text{C}$ )
- Recyclable
- LCP is flexible, and antennas fabricated on it may be rolled or molded into desired shapes
- Best mix of performance, mechanical integration compatibility, and economic viability



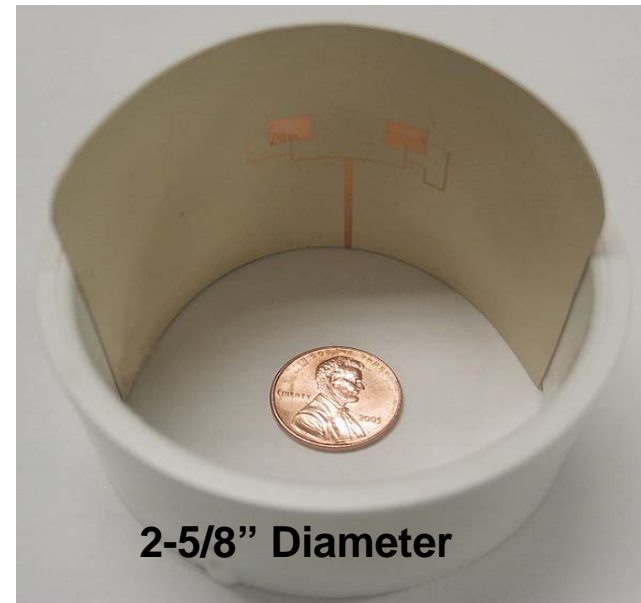
# T-Lines on LCP

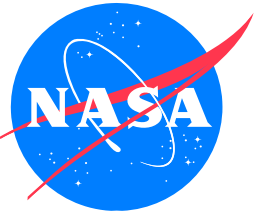


**Low loss for both microstrip and CPW lines up to 110 GHz**



# Flexibility Testing

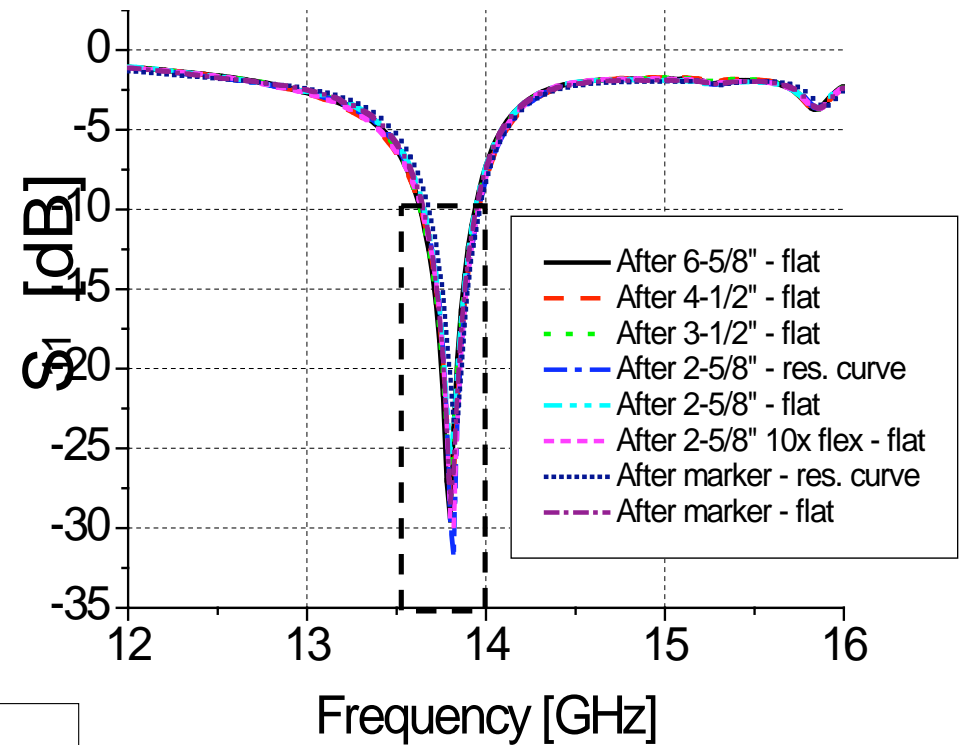
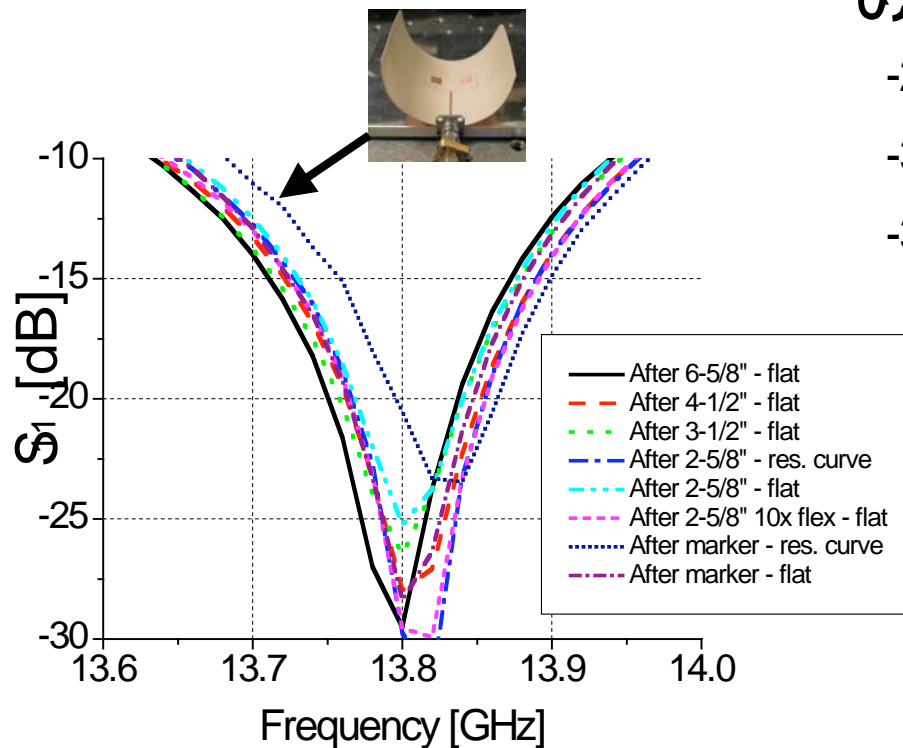




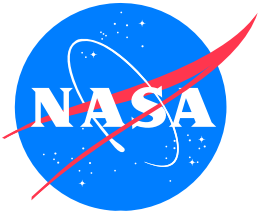
# Flexibility Testing Results



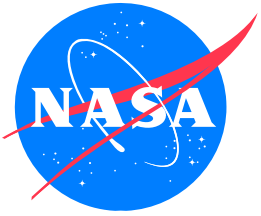
Antenna flexing does not affect performance



For extreme flex testing (marker)  
frequency shift was only 0.29%



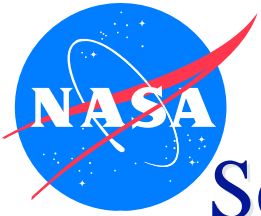
- Introduction
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# Array Optimization

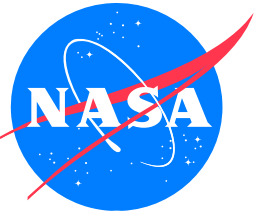


- Cross – polarization level is higher at 35 GHz
- Feed line radiation affects the 35 GHz pattern significantly
- Different configurations were tried
  - 35 on top layer with 14 embedded
  - 14 on top layer with 35 embedded
  - Different substrate thicknesses to reduce cross polarization levels, blockage effects and cross-coupling effects
  - Separating the patches and the feed layer

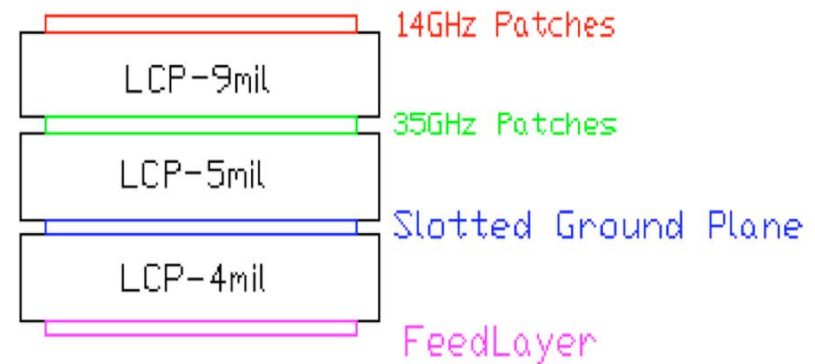
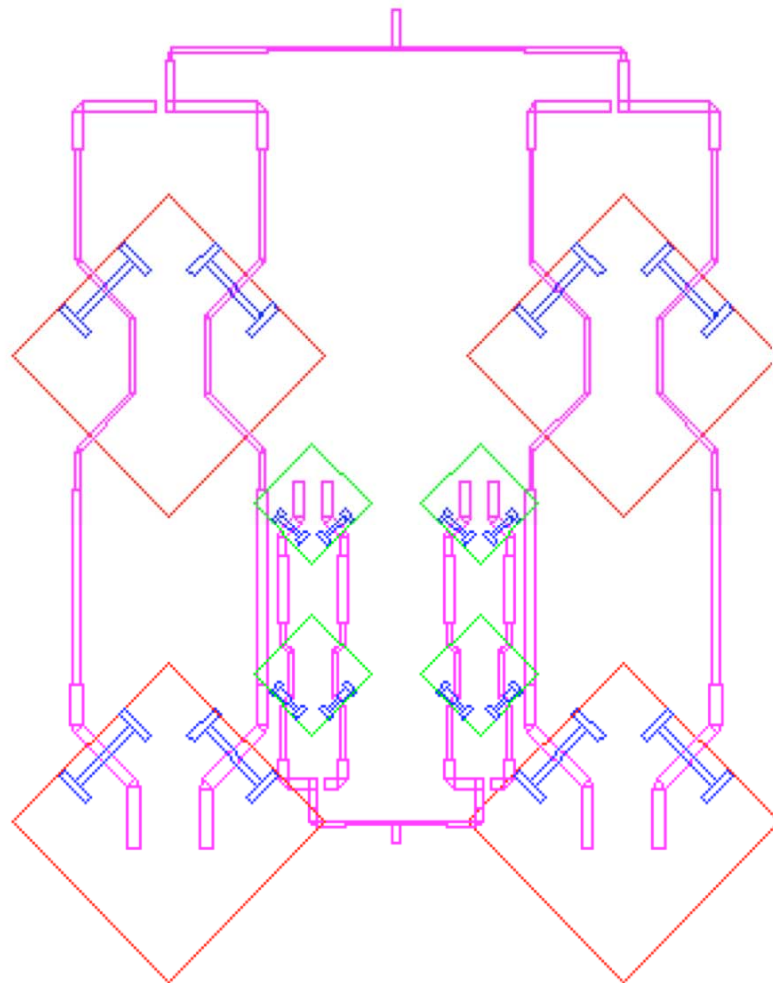


## Series Fed Aperture Coupled (SFAC) Arrays

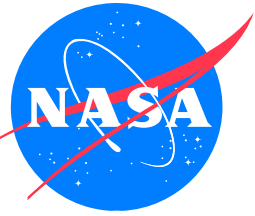
- 35 GHz patches on a thinner layer to reduce cross-polarization
- Feed networks for both the arrays on a separate layer
- Electromagnetic coupling through slotted ground
- Series feed to potentially minimize the number of switches



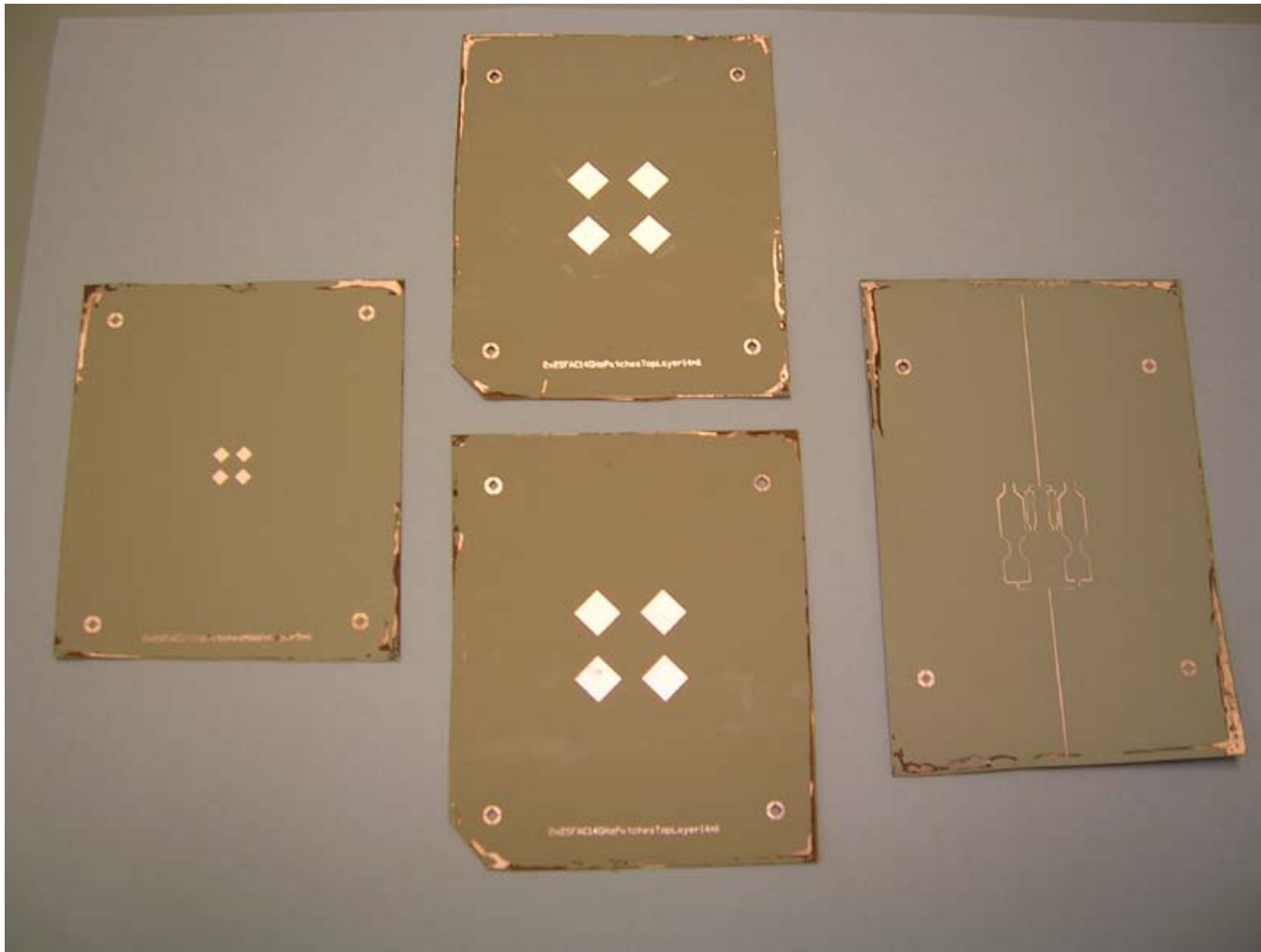
## 2X2 SFAC Array

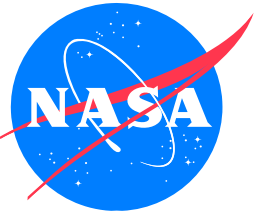


A linear sub-array is formed with two types of elements: 'Element 1', for which the feed network is terminated in open, 'Element 2', for which the feed network is terminated in a 50 Ohm load (Other antenna elements act as a load for this element) The elements within a linear sub-array are fed in series.

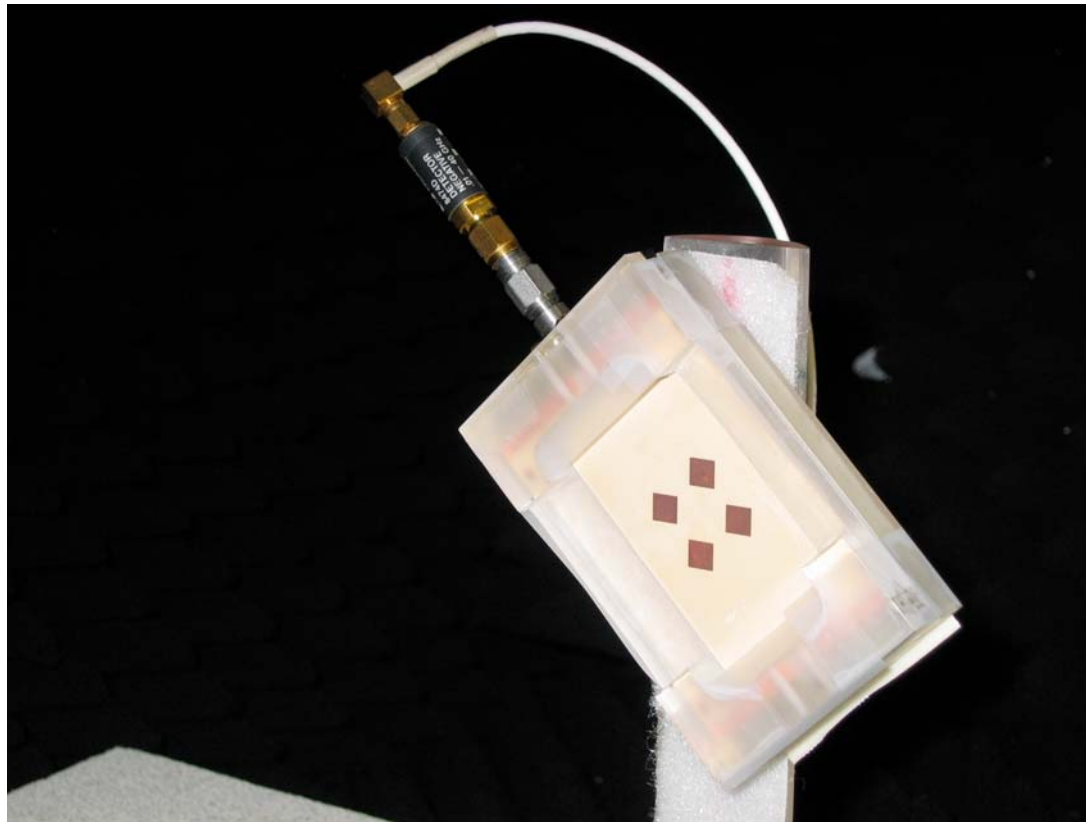


# Aperture Coupled 14/35 GHz Fabricated 2x2 Antenna Designs

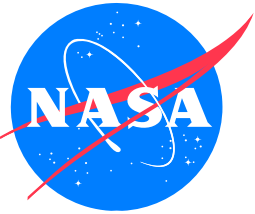




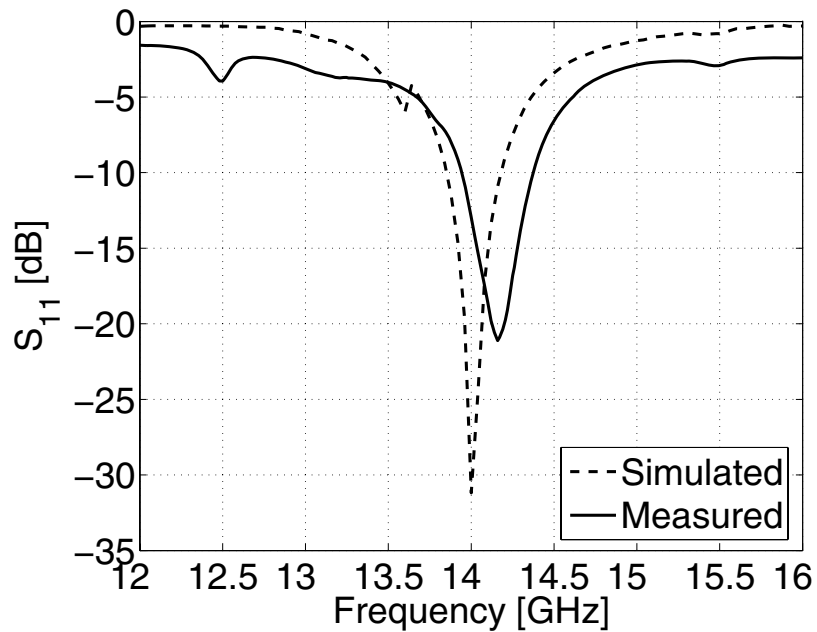
# Radiation Pattern Measurement Set-Up



Fixture, measurement, and photo done by Dr. George Ponchak at NASA, Glenn.

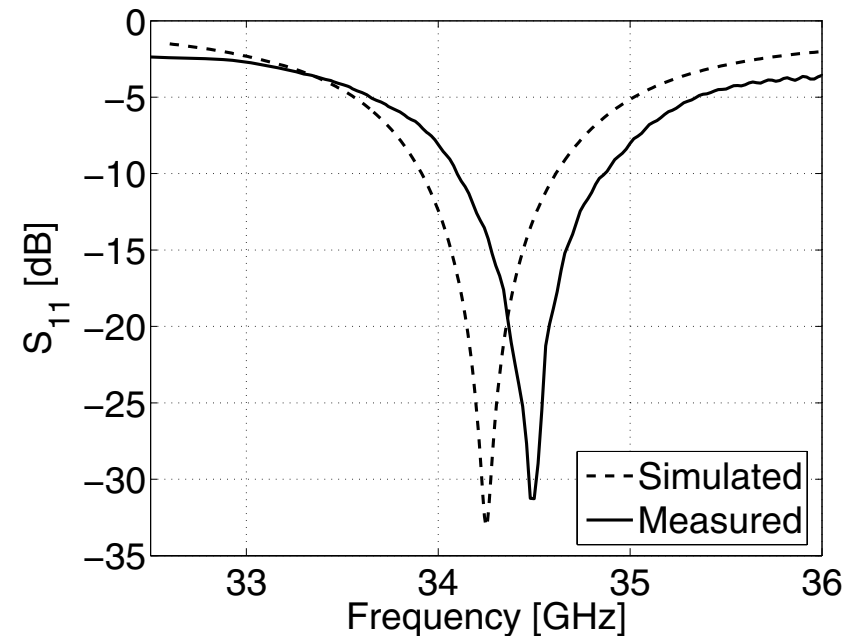


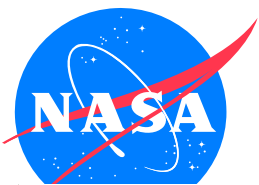
# 2X2 SFAC Array – Return Loss



Attribute	Simulated	Measured
<b>Resonant Frequency</b>	<b>34.25 GHz</b>	<b>34.5 GHz</b>
<b>Return Loss</b>	<b>-33 dB</b>	<b>-32 dB</b>
<b>Bandwidth</b>	<b>710 MHz</b>	<b>720 MHz</b>
<b>% Bandwidth</b>	<b>2%</b>	<b>2%</b>

Attribute	Simulated	Measured
<b>Resonant Frequency</b>	<b>14 GHz</b>	<b>14.16 GHz</b>
<b>Return Loss</b>	<b>-31 dB</b>	<b>-21 dB</b>
<b>Bandwidth</b>	<b>280 MHz</b>	<b>320 MHz</b>
<b>% Bandwidth</b>	<b>2%</b>	<b>2.28%</b>

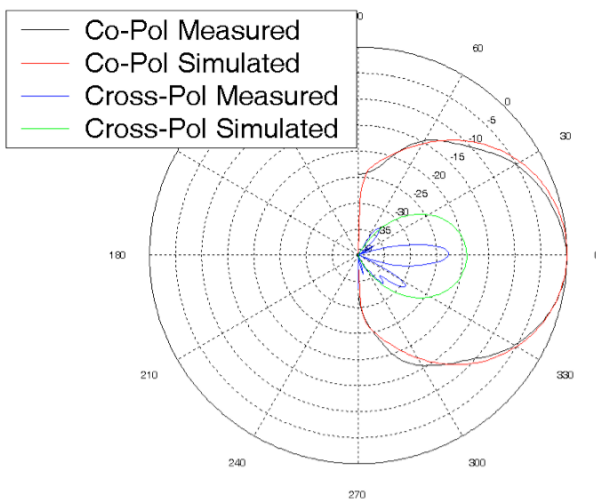




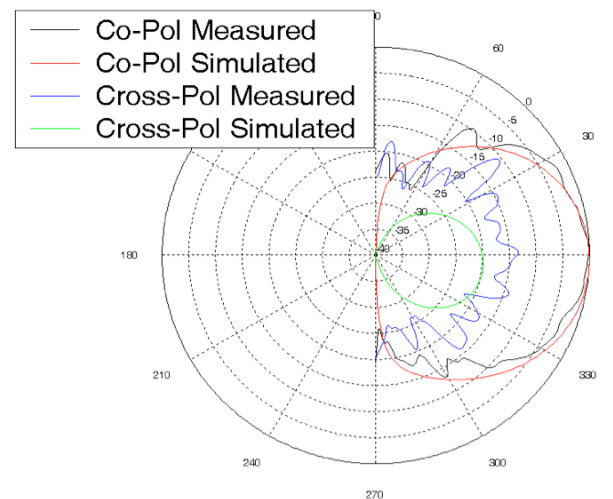
# 2X2 SFAC Array– Radiation Patterns



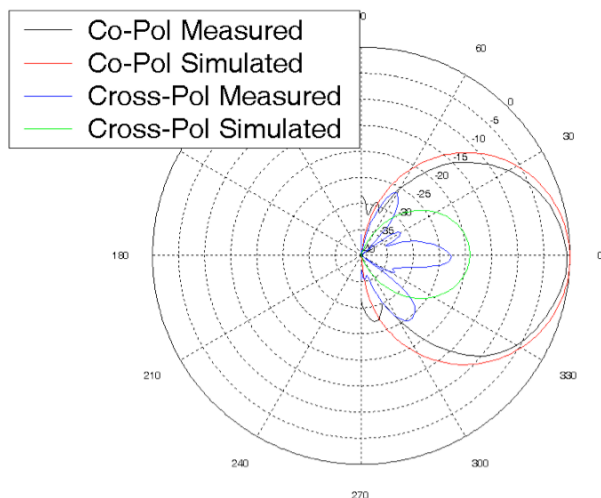
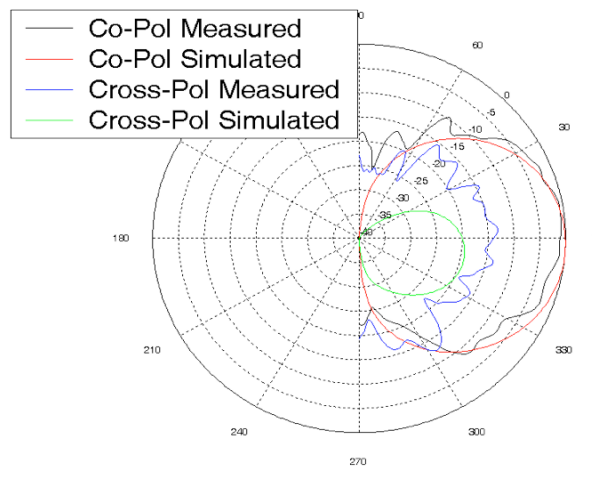
E-plane -  $14_{45}/35_{45}$  - Excitation at 14GHz



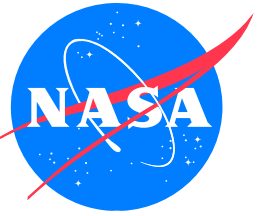
E-plane -  $14_{45}/35_{45}$  - Excitation at 35GHz



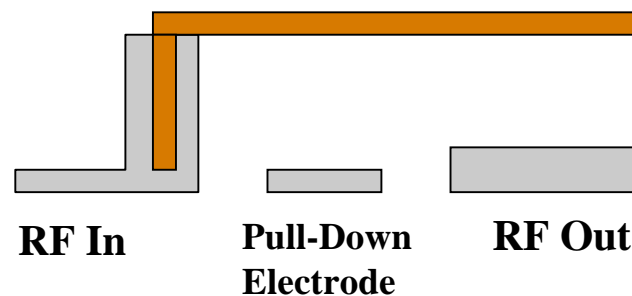
H-plane -  $14_{45}/35_{45}$  - Excitation at 35GHz



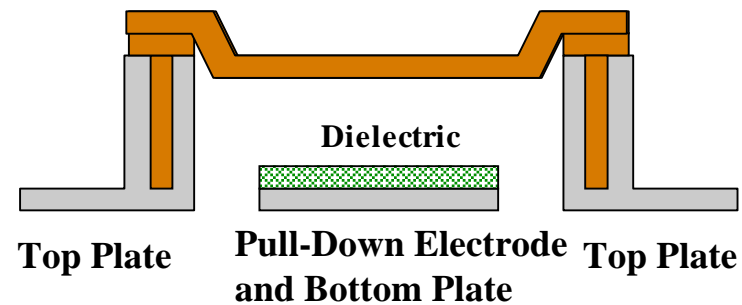
**Measured Efficiency ~ 77%**



# RF MEMS Switches

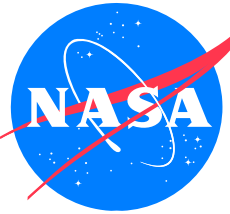


**Cantilever beam**



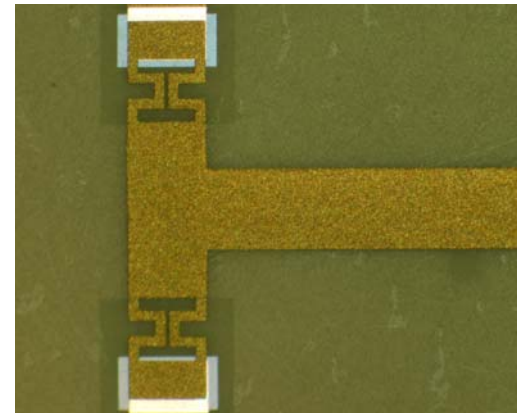
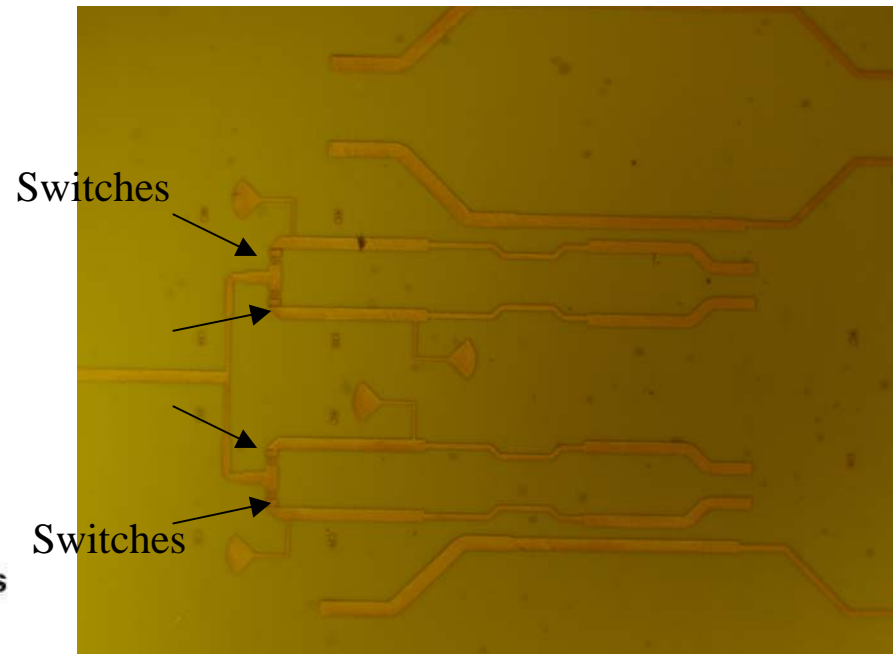
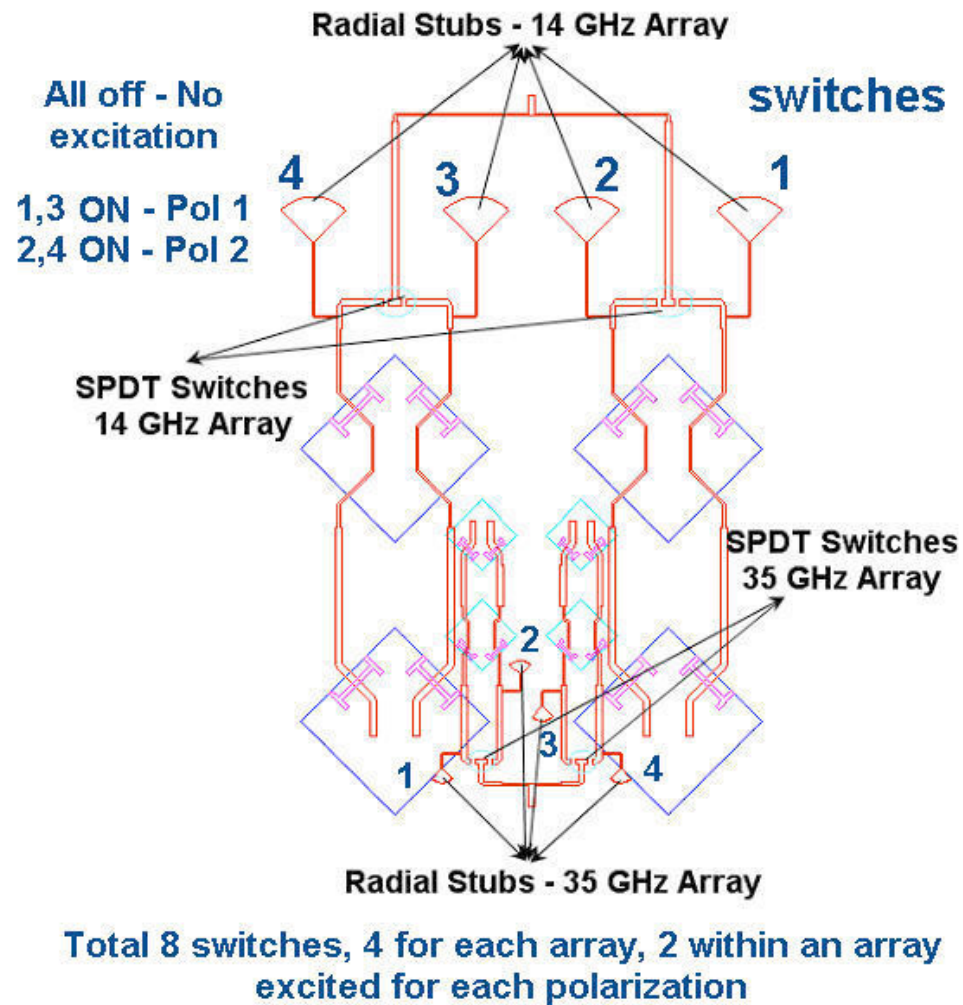
**Air-bridge**

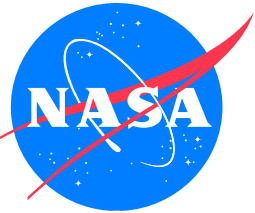
- \* Electrostatic actuation (5-60V)
- \* Low loss (up to W-band) and low cost
- \* High linearity - no distortion
- \* No power consumption
- \* Switching time 1-20  $\mu$ s
- \* IC fabrication compatible
- \* Packaging/Reliability??



# Integrated 2X2 SFAC Array with RF MEMS

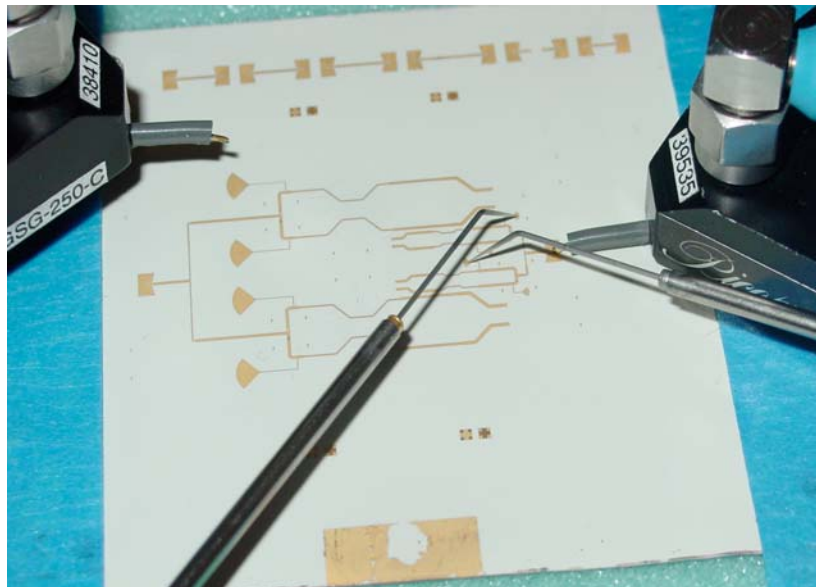
Georgia Institute of Technology



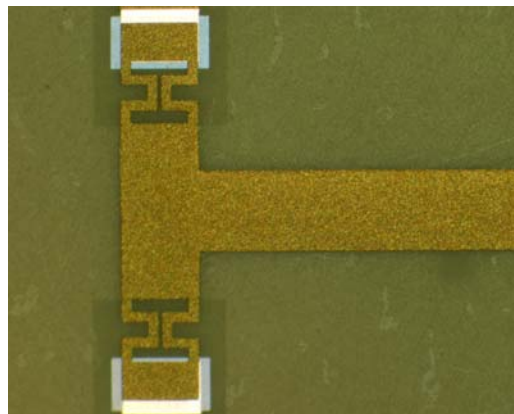
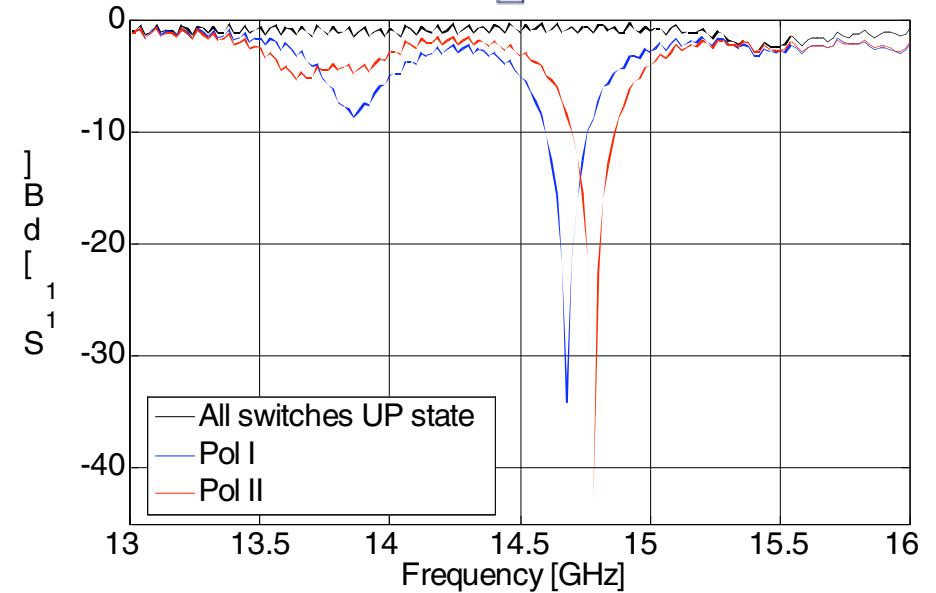


# Measured Results

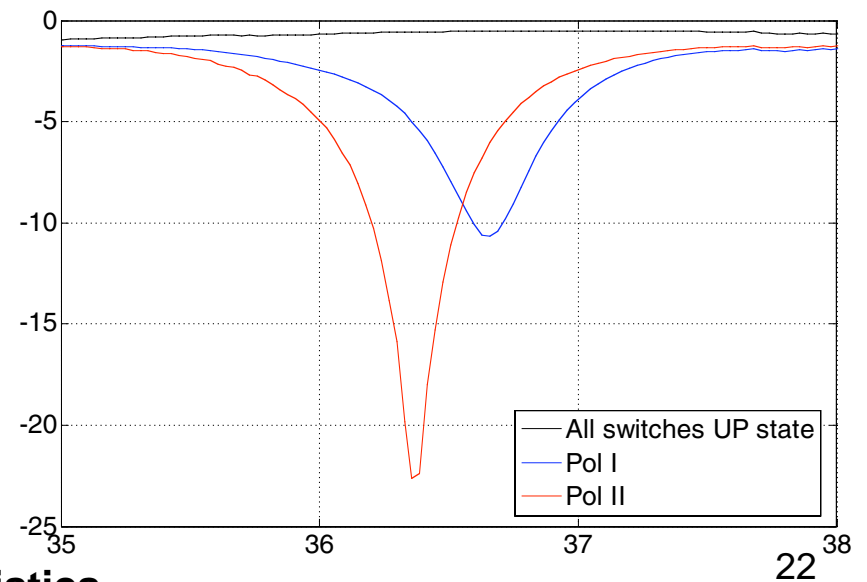
Georgia Institute of Technology



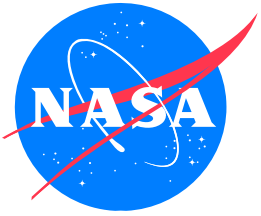
Measured Return Loss at 14 GHz



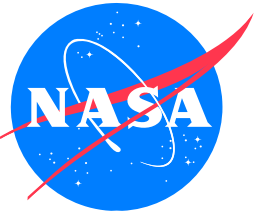
SPDT switch on LCP for polarization selection



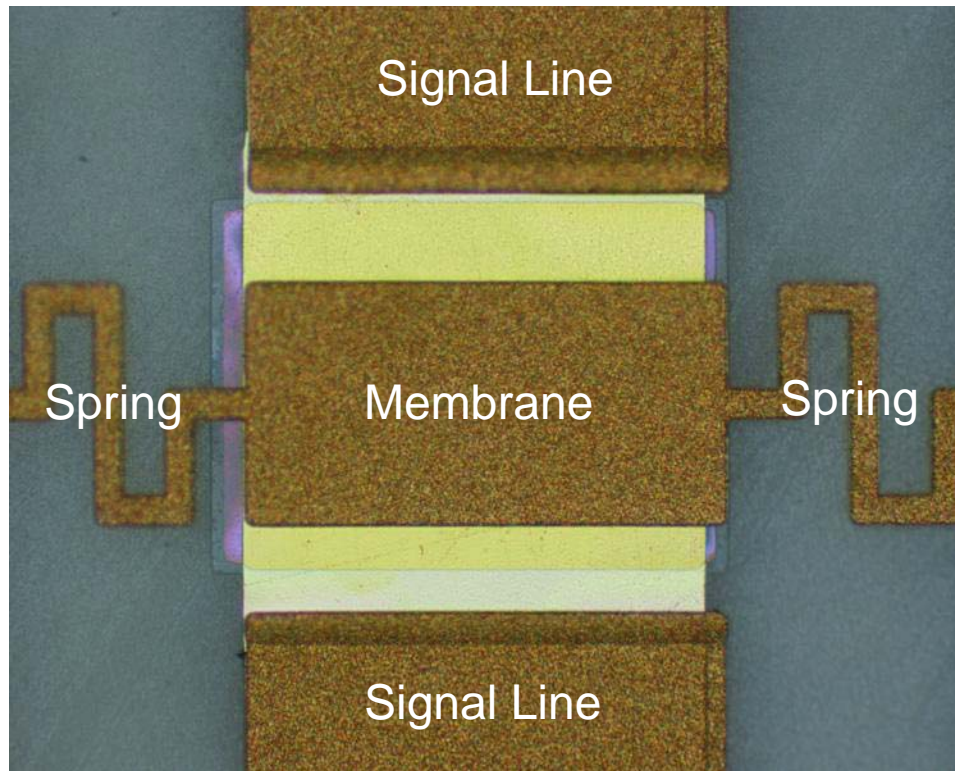
Excellent return loss characteristics



- Introduction
- LCP characterization
- 2x2 dual frequency/polarization LCP sub-arrays
- **RF MEMS Switches and Phase Shifters**
- Conclusions

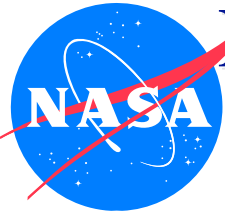


# RF MEMS Switch on LCP

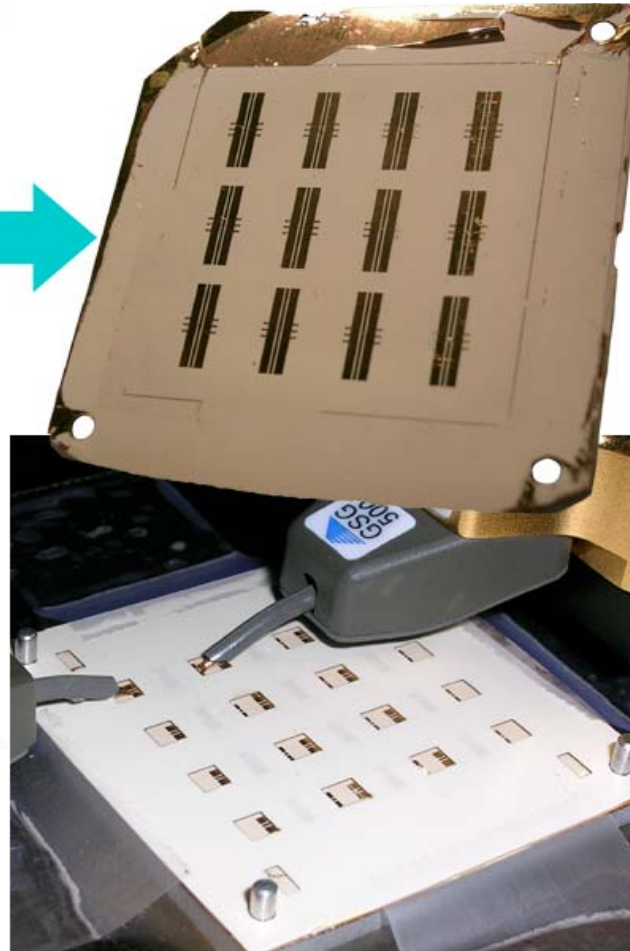
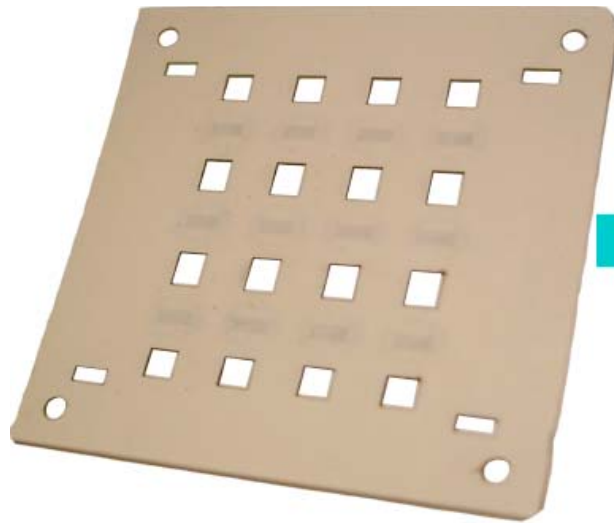


The springs anchor the membrane to the finite ground coplanar waveguide's (FGC's) ground planes [not shown]. A special process was developed to fabricate the MEMS switches on an LCP substrate.

Dark brown – electroplated gold  
Yellow – evaporated gold

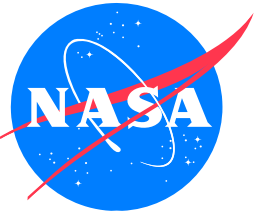


# Packaged Cavity over Air-Bridge MEMS Switches



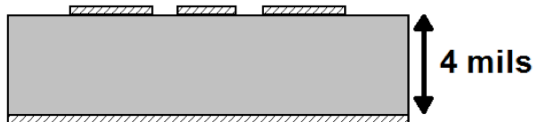
**Stack package  
and MEMS  
substrates over  
alignment pins**

2 mil deep laser-micromachined cavities on the underside of the packaging layer are aligned over an LCP substrate with MEMS switches. Measurements are made through the feedthrough holes.



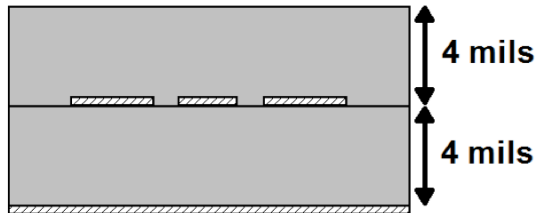
# CB-FGC Cross Sections

$Z_0 = 56.85$   
ohms



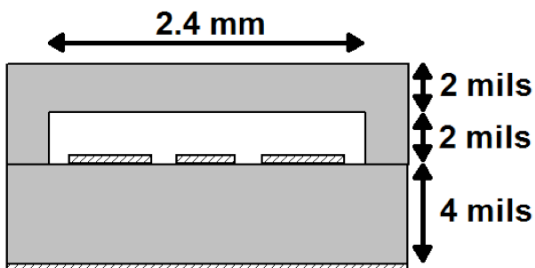
CB-FGC at feedthrough  
probing holes

$Z_0 = 52.75$   
ohms



CB-FGC with LCP  
superstrate

$Z_0 = 56.75$   
ohms



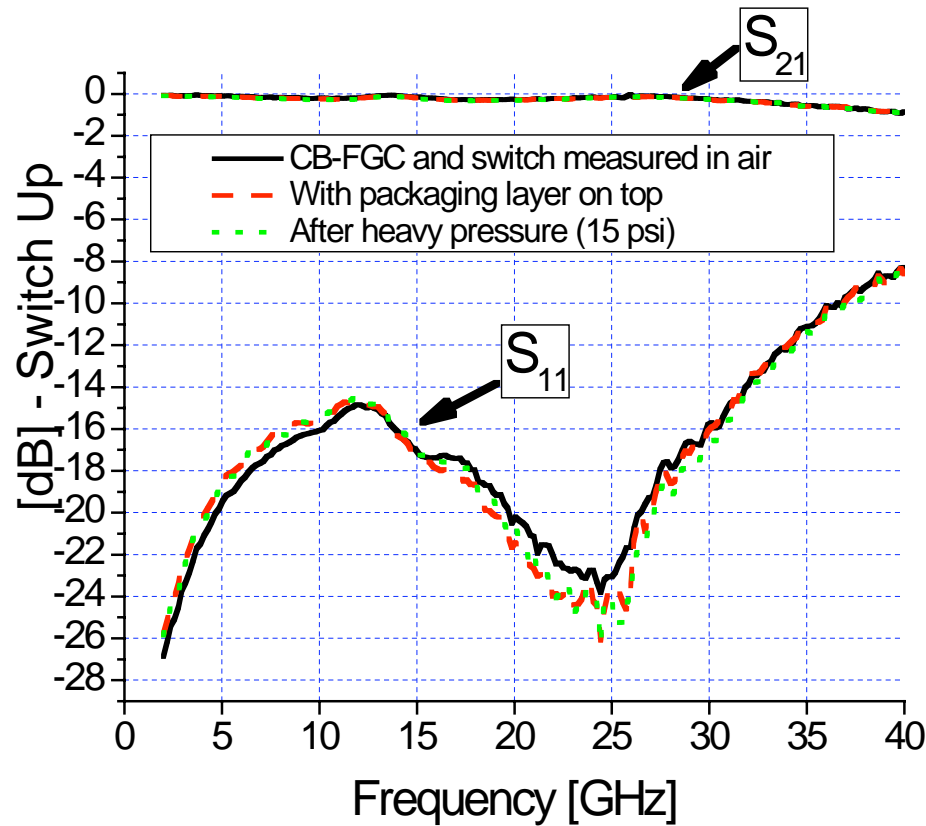
CB-FGC with  
laser machined  
LCP package

$Z_0$  varies by only  $4\Omega$   
between the three different  
transmission line cross-  
sections!

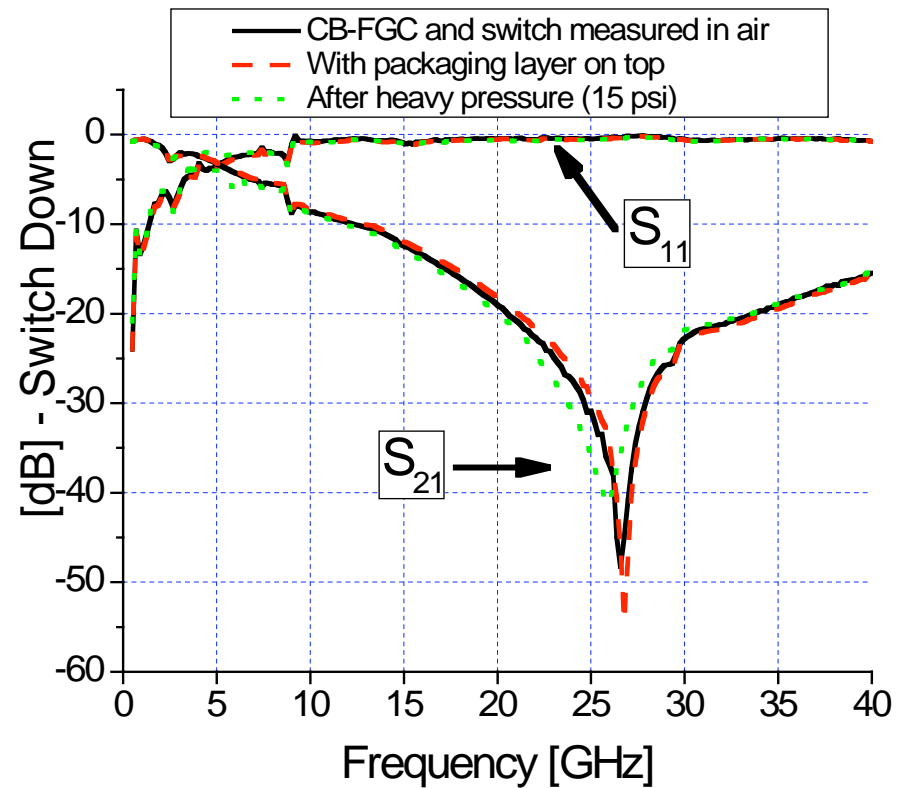
So can thin film LCP packages be designed  
with nearly arbitrary dimensions to accommodate  
the RF MEMS switches?



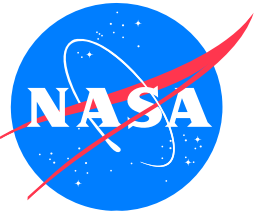
# RF MEMS Measurements: RF Characteristics of Unpackaged vs. Packaged Switches



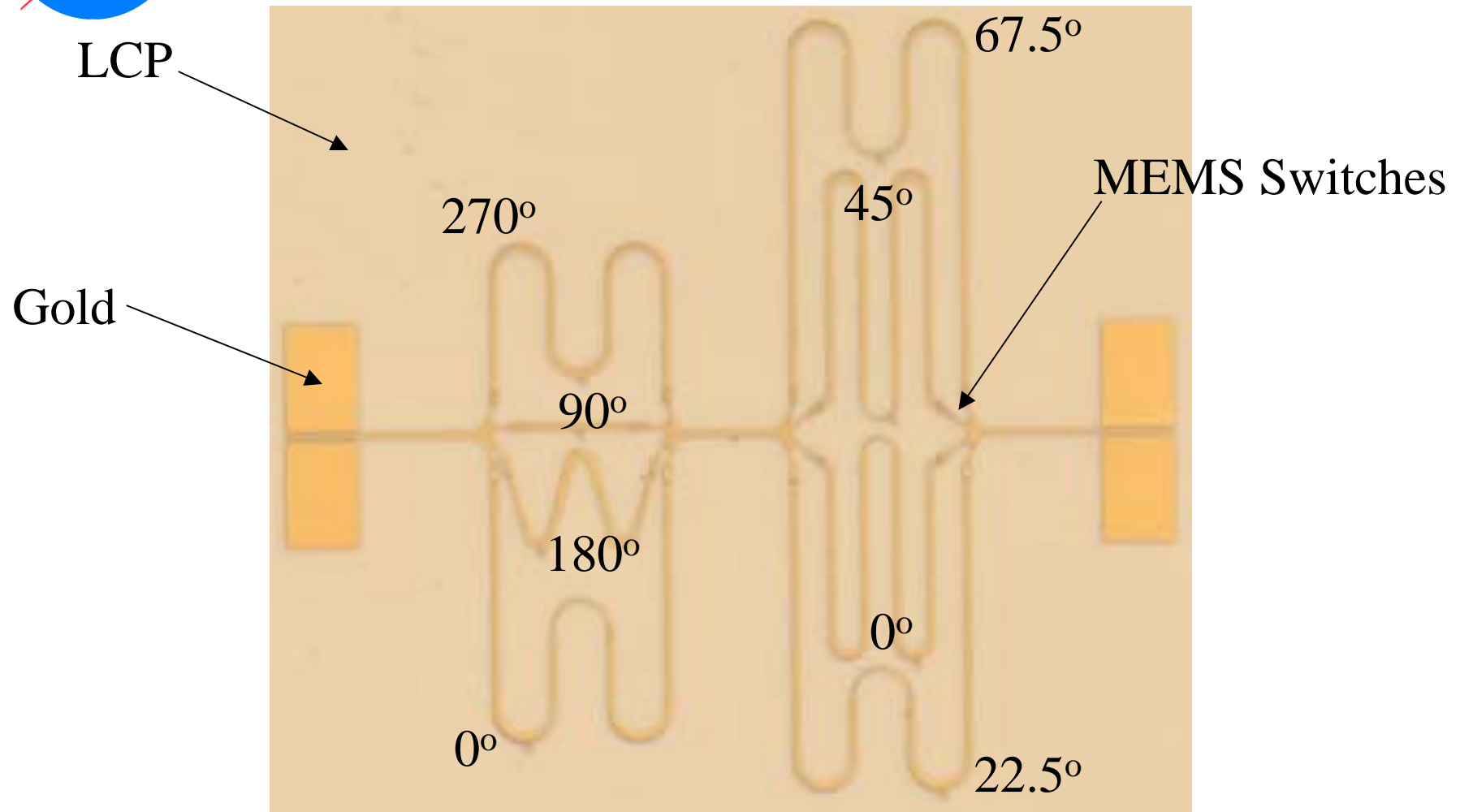
OFF



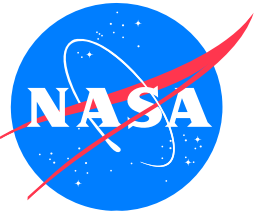
ON



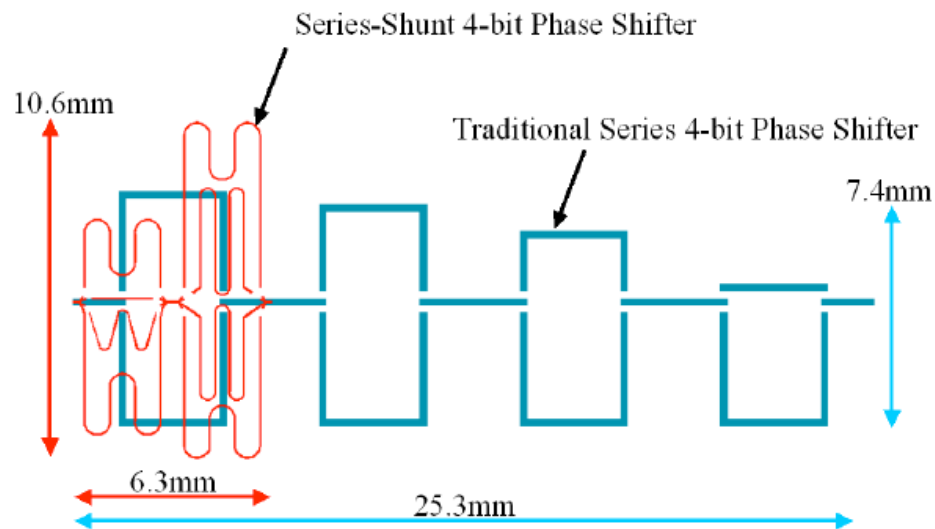
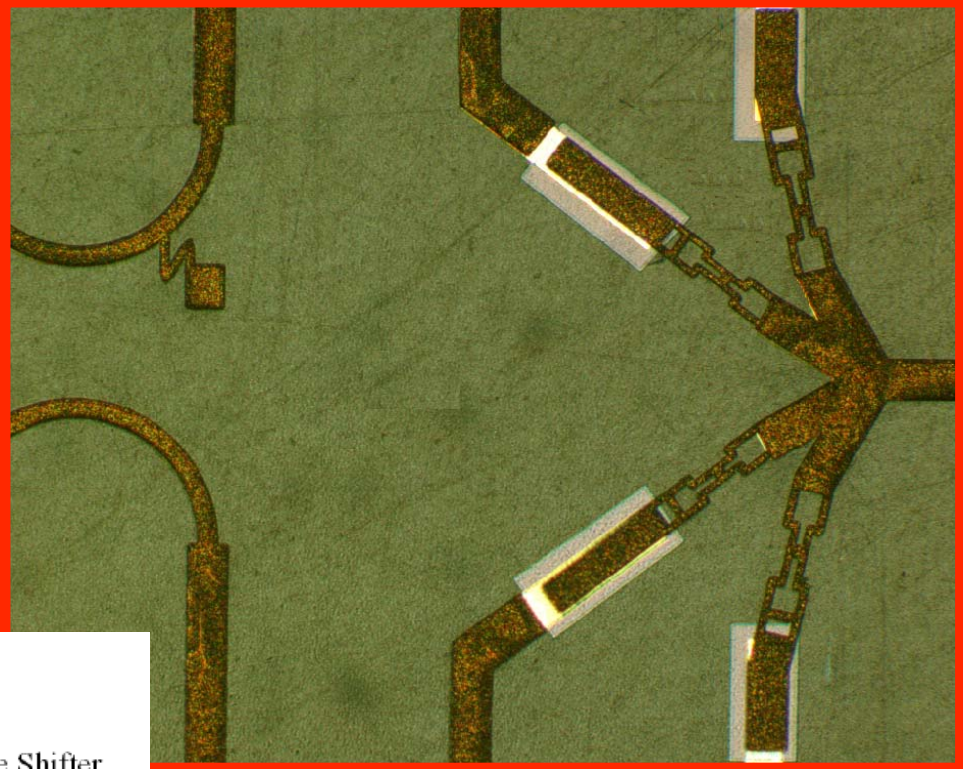
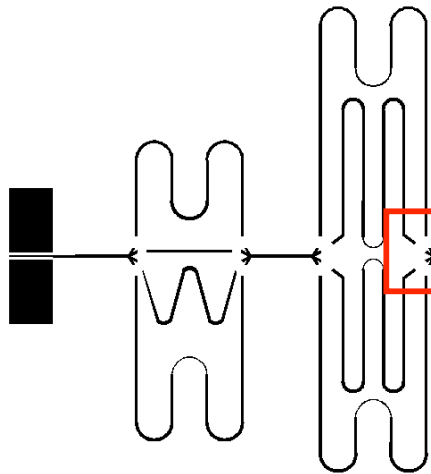
# Fabricated 4-bit Phase Shifter



Capable of phase shifts from 0° to 337.5° in 22.5° increments

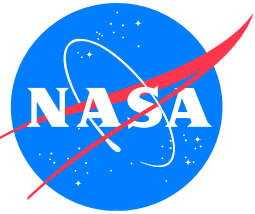


## 4-bit MEMS Shunt Phase Shifter

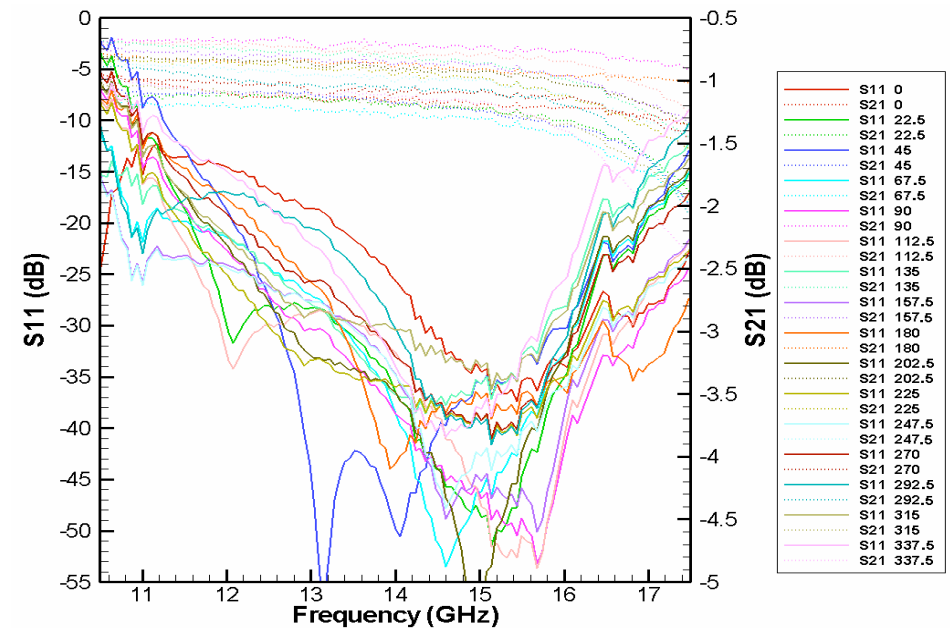
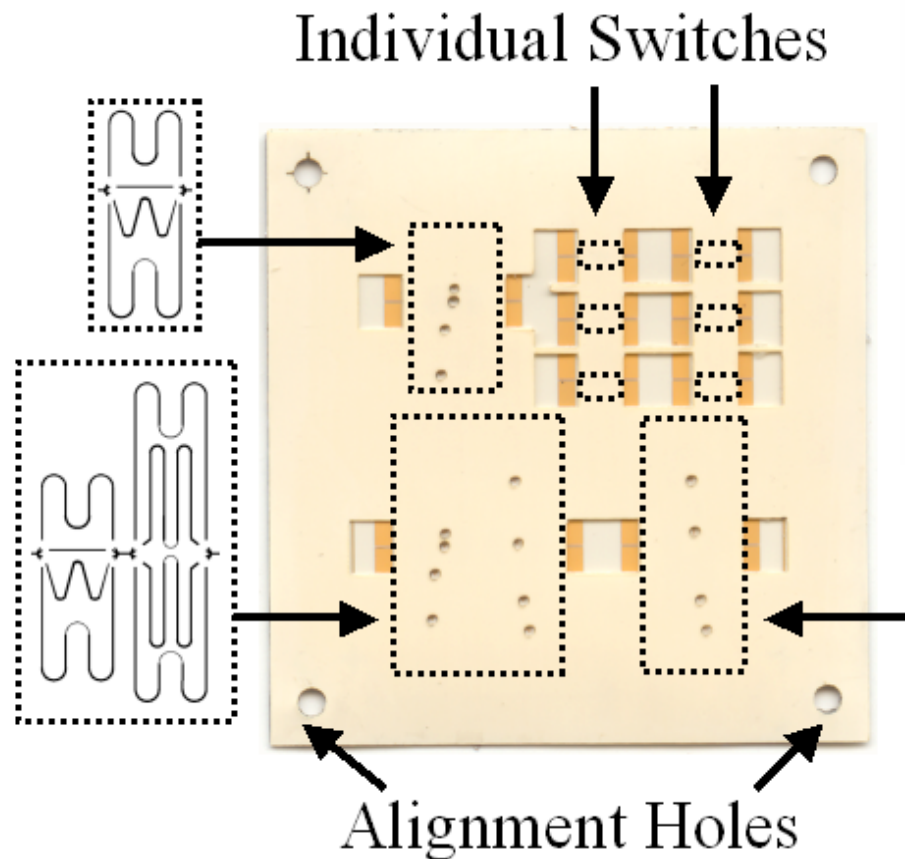


“Tree-Junction”

- One signal path IN
- Four possible signal paths OUT

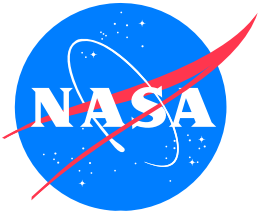


# Packaged 4-bit Phase Shifter



	Worst Case	Average	Best Case
Unpackaged S11	-20.8 dB	-30.9 dB	-45.0 dB
Unpackaged S21	-1.22 dB	-0.95 dB	-0.66 dB
Packaged S11	-19.7 dB	-32.5 dB	-45.3 dB
Packaged S21	-1.21 dB	-0.96 dB	-0.69 dB
Unpackaged Phase Error	8.25°	3.96°	0.34°
Packaged Phase Error	17.07°	6.57°	1.38°
S21 Loss Variation	0.045 dB	0.013 dB	0.0022 dB
S21 Phase Variation	9.77°	3.16°	0.27°

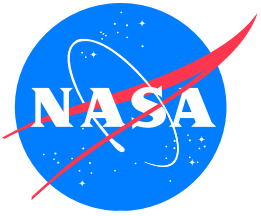
**Loss ~ 0.24 dB/bit @ 14 GHz**  
**Shift in beam < 1° for error ~ 4-5°**



## Conclusions



- Demonstration of the excellent electrical and packaging performance of LCP organic materials up to 110 GHz
- Development of 2x2 dual frequency/polarization array (14/35 GHz) on lightweight, flexible, multilayer LCP substrates with RF MEMS switches
- Development of first packaged organic MEMS switch with low loss up to 40 GHz ( $<0.3$  dB)
- Development of first low loss packaged 4-bit RF MEMS phase shifter (0.24 dB/bit @ 14 GHz)
- *Multilayer SOP RF front ends a viable candidate for NASA high-frequency systems and applications*



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